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LM01 Mirror Magnet Test Summary

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Content:

1. Introduction

LM01 is a 2m long mirror magnet assembled at Fermilab Technical Division as part of the high-field accelerator magnet development program. One of the two half-coils of this dipole magnet was replaced with the iron-blocks (magnetic mirror), the other coil was made of powder-in-tube (PIT) 1-mm Nb_3Sn strands. The magnet was installed into the Fermilab Vertical Magnetic Test Facility (VMTF) dewar on May 4th, 2007. Electrical checkout and CVT panel configuration were completed by May 7th and dewar was filled with liquid helium on May 10th. LM01 magnet went trough only one thermal test cycle which ended on May 16th. The expected short sample limit for the quench current at 4.5K was 21500A assuming 10% cable degradation.

2. Quench History

A series of trips at the beginning were induced by balancing the analog quench detection (AQD) system. One of the AQD modules for *Copper* leads was replaced with the spare one. Quench protecting system was tested using manual quench at 5000A. HFU2 strip heater was fired at 300V capacitor voltage and 0ms delay, dump delay was set to 25ms. Both strip heaters – one in protecting and another in testing mode – fired at the appropriate times.

The magnet test program started with quench training at 4.5 K temperature with 20A/s ramp rate and acceleration 10A/s^2. The quench detection threshold was set to 500 mV. Dump delay was set to 1ms, two strip heaters were set in protection mode at 400V with delay set to 1ms.

Training at 4.5K was started with 3 quenches at VMTF superconducting leads detected by the AQD (1st and 3rd quenches) or digital quench detection (DQD, 2nd quench) system. Therefore first real quench (4th quench) was detected at 17862A in the innermost turn of the inner layer of the coil. One should mention that most voltage taps were mounted on the inner layer only. In addition we had voltage tap segments in the region of splices between NbTi and Nb_3Sn conductors on both inner and outer layers.

At the ninth and following 3 quenches AQD system tripped on VMTF *Copper* leads at about 18800A. We decided to balance AQD circuits at 5000A and then at 10000A. After this balancing training went smoothly and in 16 more quenches (2 of them were again trips at VMTF superconducting leads) we reached the critical current limit value. The final quench at 4.5K temperature was at 20966A.

After the ramp rate study (see section 3) the magnet was cooled down to 2.2 K temperature and the training started from 21085A followed by a significant step back to 18825A. The quench current increased to 21500A in 6 quenches. Quenches 42 and 44 most likely were originated from the outer layer of the coil where we missed the voltage taps to identify quench location.

The quench program was completed with few more quenches again at 4.5K. First one confirmed that the magnet had reached its limit at 4.5K and the quench current was in the same range as it was before the 2.2K training. Following 2 ramps resulted again in trips at VMTF superconducting leads.

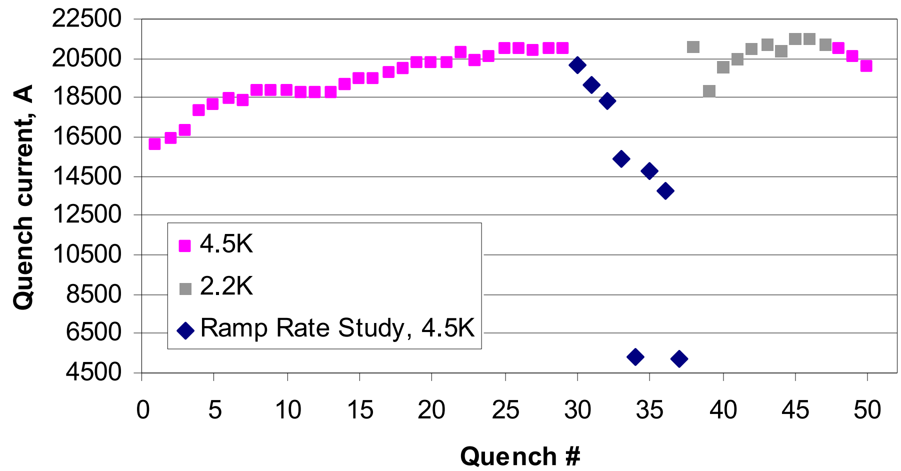

Fig.1. LM01 quench history

Voltage tap segments on the innermost turn of the inner layer (11th turn from the coil midplane) showed most of the quenches during the training and for all quenches at the plateau.

The quench history is presented in Figure 1 and in the following table 1. This table has been generated by processing the quench files. Comments have been added subsequently based on notes taken during the test.

Same quench history in Figure 2 shows that several quenches were detected at the VMTF superconducting and *Copper* leads.

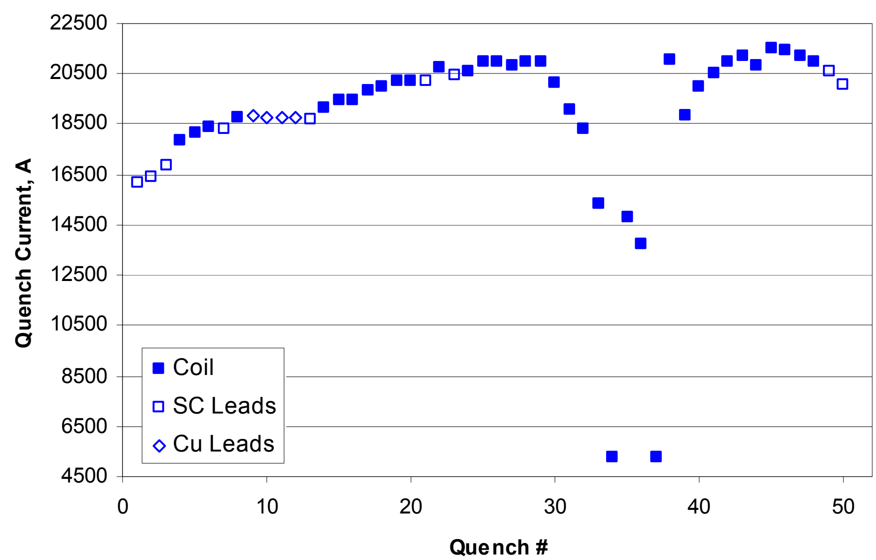

Fig.2. LM01 quench history: empty squares and rhombs correspond to trips at VMTF superconducting (SC) or *Copper* (Cu) leads.

For comparison the quench history for the 1m long mirror magnet HFDM03 is also shown in Figure 3. Strand parameters and coil fabrication technology is the same for both mirror magnets.

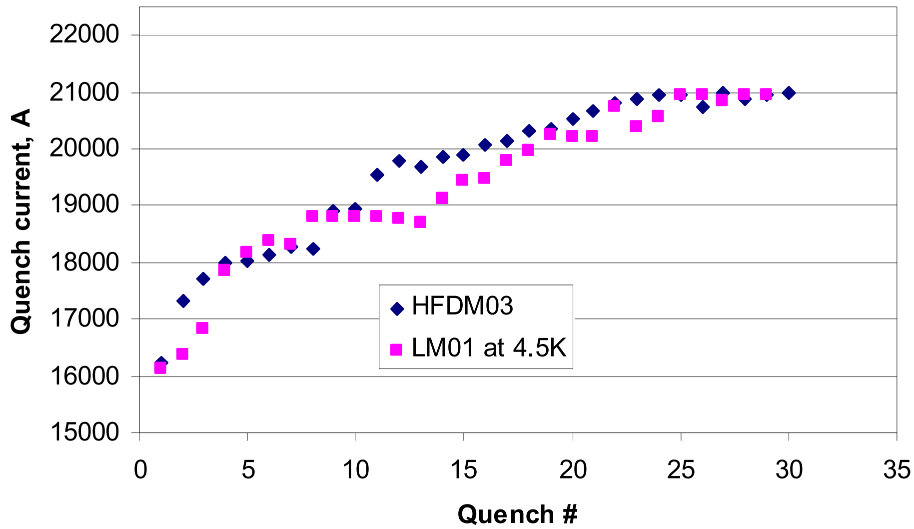

Fig.3. LM01 (2m long mirror magnet) quench history at 4.5K. The quench history for the 1m long mirror magnet HFDM03 is also shown.

3. Ramp Rate Dependence

Ramp rate dependence studies were performed at 4.5 K. Results normalized on their maximum quench current at dI/dt=20A/s are shown in Fig.4. Quench current decreases with increasing ramp rate.

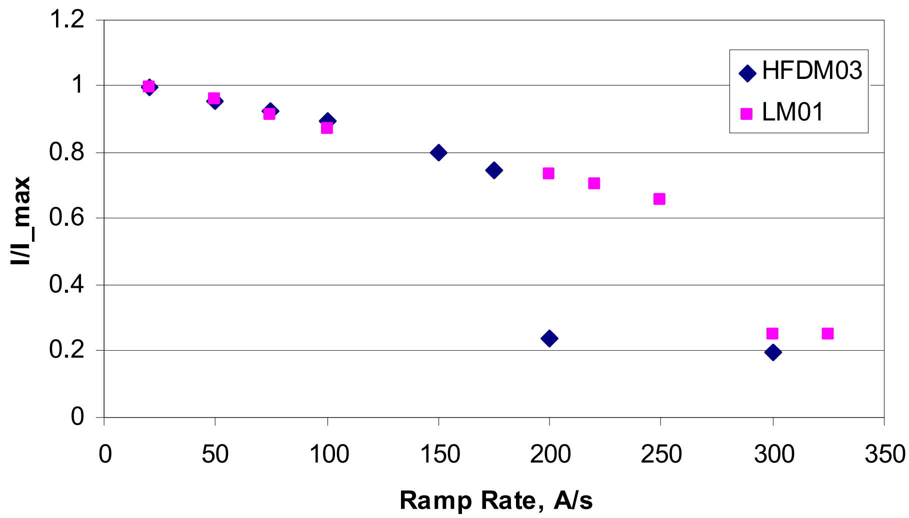

Fig.4. Ramp rate dependence of magnet quench current at 4.5K. The same dependence for the 1m long mirror magnet HFDM03 is also shown.

File	#	Iq	dI/dt	quench time	MIITs	QDC	1st VSeg	trise	T (Bot)	T (Top)	Comment
lm01.Quench.070510163817.062		1730	-2	0.0000	0.1	WcoilGnd	11LER_11RER	-0.0003	4.487	4.484	at 500 A - we will need to do this again.ü
lm01.Quench.070510164332.085		119	21	-0.0020	-	WcoilIdot	11LER_11RER	0.0006	4.491	4.486	it's still early in the day.4E-03
lm01.Quench.070510172524.951		597	0	0.0000	0.05	WcoilGnd	OS30_OC	-0.0003	4.508	4.523	
lm01.Quench.070510175843.967		1069	0	0.0000	0.06	WcoilGnd	11LEL_11LER	-0.0003	4.461	4.450	Cu-I AQD had to be changed, but the threshold was not precisely known. This ramp to 1000 A had only the copper signal, so unbalanced, to see what threshold was - it was 40mV, and subsequently was reset to 30mV.
lm01.Quench.070510182141.489		5011	0	-0.1136	3.95	HcoilHcoil	IS30_3AU	-0.1131	4.431	4.429	quench protectin test with 25ms delayed dump, heater 2 fired at 300 V to induce a quench and check protection and characterization systems. no heater delay
lm01.Quench.070510192634.473	1	16149	20	-0.0168	7.73	SlWcoil	OS30_OC	0.0008	4.435	4.438	AQD_Leads tripped at I=16140 A, Rate=20A/s, T=4.4K.
lm01.Quench.070510200456.943	2	16370	19	-0.0202	8.83	SlWcoil	IC_IS31	-0.0126	4.437	4.440	I=16399A, T=4.4K, Rate 20A/s. Now dqd_leads trip.ü
lm01.Quench.070511114747.128	3	16851	20	-0.0064	5.46	SlWcoil	IC_IS31	-0.0038	4.443	4.447	AQD_leads imdiced quench at I=16840A. Rate=20A/s, Te=4.4K.
lm01.Quench.070511123738.510	4	17874	20	-0.0034	5.23	WcoilGnd	OS31_OS30	0.0008	4.453	4.456	Quench 4: AQD_Coil trip at ~17850A, Ramp rate=20A/s, Te=4.4K.
lm01.Quench.070511132304.586	5	18182	20	-0.0048	5.88	HcoilHcoil	11LER_11RER	-0.0055	4.456	4.461	Quench 5 at I=18170 A, Ramp rate 20A/s, T=4.4k. DQD_Coil trip.
lm01.Quench.070511142430.190	6	18403	20	-0.0043	5.81	HcoilHcoil	11LER_11RER	-0.0055	4.454	4.460	Quench 6: I=18388 A with ramp rate 20A/s, T=4.4K.
lm01.Quench.070511152343.519	7	18333	20	-0.0144	8.93	SlWcoil	IC_IS31	-0.0077	4.478	4.487	Quench 7 at I=18319A, ramp rate=20A/s, T=4.45K.
lm01.Quench.070511162933.052	8	18809	20	-0.0045	6.1	HcoilHcoil	11LER_11RER	-0.0053	4.475	4.473	Quench 8 at I=18793A, ramp rate 20A/s, T=4.45K. dqd detected quench.
lm01.Quench.070511172704.905	9	19188	19	0.0000	4.21	WcoilGnd	11LEL_11LER	0.0006	4.457	4.454	Quench 9 at I=18817.3A, rate 20A, T=4.4K. AQD_Leads detected.
lm01.Quench.070511180603.885	10	18834	20	-0.0003	4.28	WcoilGnd	IC_IS31	0.0006	4.457	4.456	Quench 10 at I=18799.1A, ramp rate 20A/s. T=4.4K. Aqd_leads detected quench.
lm01.Quench.070511184816.124	11	19086	20	0.0000	4.2	WcoilGnd	IC_IS31	0.0006	4.445	4.448	Quench 11, I = 18788 A, ramp = 20 A/s, T = 4.5 K
lm01.Quench.070511193046.142	12	18888	20	0.0000	4.2	WcoilGnd	IC_IS31	0.0004	4.459	4.459	Quench 12, I = 18784 A, Ramp = 20 A/s, T = 4.5 K
lm01.Quench.070511203210.756	13	18710	20	-0.0106	7.92	SlWcoil	11LEL_11LER	0.0006	4.451	4.455	Quench 12 at I=18670A , ramp rate 20A/s, T=4.45K.

lm01.Quench.070511210540.323	14	19131	19	-0.0043	6.17	HcoilHcoil	11LER_11RER	-0.0049	4.453	4.458	Quench 14 at I=19113A, rate 20A/s, T=4.45K. Aqd_coil detected quench.
lm01.Quench.070511214325.772	15	19436	20	-0.0045	6.4	HcoilHcoil	11LER_11RER	-0.0045	4.454	4.459	Quench 15 (Aqd detected) at I=19425A. Ramp rate 20A/s, T=4.45K.
lm01.Quench.070512103341.632	16	19484	20	-0.0035	6.14	HcoilHcoil	11LER_11RER	-0.0043	4.463	4.468	Quench 16 at I=19476A, T=4.45K, ramp rate=20A/s. Quench was detected in Aqd_HalfCoils.
lm01.Quench.070512112644.246	17	19803	20	-0.0035	6.25	HcoilHcoil	11LER_11RER	-0.0036	4.463	4.467	Quench 17 at I=19794A, ramp rate 20A/s, T=4.45K. Aqd_coild detected.
lm01.Quench.070512121151.312	18	19984	20	-0.0136	10.36	HcoilHcoil	IS30_3AU	-0.0112	4.461	4.465	Quench 18 detected by Aqd_halfcoils at I=19975.8A., ramp rate 20A/s, T=4.45K.
lm01.Quench.070512130237.052	19	20244	20	-0.0028	6.15	WcoilGnd	11REL_CC	-0.0034	4.459	4.465	Quench 19 was at I=20235.2A, T=4.4K, ramp rate 20A/s.
lm01.Quench.070512151225.085	20	20230	20	-0.0025	6.09	HcoilHcoil	11LEL_11LER	-0.0020	4.449	4.458	Adq+coil detected quench # 20 at I=20219A, T=4.4K, ramp rate = 20A/s.
lm01.Quench.070512160206.020	21	20235	19	-0.0095	8.58	SlWcoil	IC_IS31	0.0004	4.454	4.461	quench 21 I=20213A, T=4.4K, ramp rate 20A/s.
lm01.Quench.070512164319.918	22	20765	19	-0.0027	6.38	HcoilHcoil	11LEL_11LER	-0.0017	4.455	4.463	aqd_coil detected quench at I=20755A., T=4.45K, ramp rate 20A/s.
lm01.Quench.070512171557.003	23	20416	20	-0.0092	8.62	SlWcoil	11LEL_11LER	0.0004	4.454	4.463	quench 22 was detected by aqd_leads at I=20404A, T=4.45K, ramp rate was 60A/s upto 15100A and then 20A/s.
lm01.Quench.070512180357.105	24	20591	19	-0.0022	6.11	HcoilHcoil	11REL_CC	-0.0018	4.454	4.462	Quench 24 at I=20580A, T=4.45K, ramp rate 20A/s.
lm01.Quench.070514105322.026	25	20947	20	-0.0022	6.35	HcoilHcoil	11LER_11RER	-0.0017	4.473	4.470	Quench 25 at I=20937.5A, T=4.45K, ramp rate 20A/s.
lm01.Quench.070514114324.661	26	20949	20	-0.0025	6.43	HcoilHcoil	11LER_11RER	-0.0021	4.471	4.468	quench 26 at I=20936.3A, T=4.45K, ramp rate 20A/s. aqd_halfcoil detected quench.
lm01.Quench.070514122908.908	27	20847	20	-0.0031	6.61	HcoilHcoil	11LEL_11LER	-0.0021	4.469	4.467	Quench 27 AT I=20836A, T=4.45K, ramp rate 20A/s.
lm01.Quench.070514131936.016	28	20963	20	-0.0024	6.33	HcoilHcoil	11LEL_11LER	-0.0021	4.460	4.459	Quench detected by aqd_halfcoils was at I=20948.6A, T=4.44K, ramp rate=20A/s.
lm01.Quench.070514145946.328	29	20966	20	-0.0022	6.32	HcoilHcoil	11LER_11RER	-0.0017	4.455	4.456	quench 29 detected by aqd_coils, I=20951.7A, T=4.44K, ramp rate 20A/s.
lm01.Quench.070514161313.309	30	20151	50	-0.0024	6.03	HcoilHcoil	11LEL_11LER	-0.0036	4.440	4.437	Ramp rate study: quench at I=20137A for rakmp rate of 50A/s. T=4.45K.
lm01.Quench.070514170515.108	31	19119	76	-0.0027	5.58	WcoilGnd	11LEL_11LER	-0.0038	4.430	4.430	ramp rate=75A/s, quench curremt 19105A, T=4.45K.
lm01.Quench.070514173149.581	32	18324	99	-0.0027	5.2	HcoilHcoil	11LEL_11LER	-0.0041	4.431	4.430	Ramp rate study: I=18312.2A, Ramp rate=100A/s, T=4.44K.
lm01.Quench.070514175949.236	33	15354	200	-0.0039	4.19	HcoilHcoil	11LEL_11LER	-0.0057	4.428	4.423	Ramp rate study: quench 33 at I=15341.7A, with rate=200A/s, T=4.44K.

lm01.Quench.070514182649.898	34	5128	0	-0.5242	14.8	WcoilGnd	IS30_3AU	-0.0480	4.427	4.418	Ramp rate study: quench 34 at I=5269.4A, rate=300A/s, T=4.44K.
lm01.Quench.070514185539.035	35	14781	220	-0.0042	4.02	WcoilIdot	11LEL_11LER	-0.0057	4.430	4.426	Ramp rate study: quench 35, rate=220A/s, I=14772.1A. T=4.44K.
lm01.Quench.070514194139.542	36	13728	250	-0.0071	4.08	HcoilHcoil	11RER_11REL	-0.0071	4.432	4.427	Ramp rate study: quench 36 at I=13712.6A when ramp rate was 250A/s. T=4.44K.
lm01.Quench.070514200510.727	37	5085	316	-0.4807	13.38	WcoilGnd	IS30_3AU	-0.0482	4.431	4.424	End of ramp rate studies: quench 37 at I=5229A for the rate=325A/s. T=4.4K.
lm01.Quench.070515120215.276	38	21101	20	-0.0021	6.34	WcoilGnd	11LEL_11LER	-0.0029	2.161	2.160	Quench 38 at I=21085.9A, T=2.16K, ramp rate=20A/s.
lm01.Quench.070515131308.381	39	18835	20	-0.0028	5.49	WcoilIdot	11LER_11RER	-0.0034	2.161	2.159	quench 39 at I=18830A, T=2.16K, ramp rate=20A/s.
lm01.Quench.070515140849.911	40	20035	20	-0.0022	5.91	WcoilIdot	11LER_11RER	-0.0031	2.160	2.158	Quench 40 was at I=20019A, T=2.16K, Ramp rate=20A/s.
lm01.Quench.070515150235.806	41	20507	20	-0.0017	5.86	WcoilIdot	11LER_11RER	-0.0025	2.160	2.159	quench 41 at I=20495.4A, T=2.16K, ramp rate=20A/s.
lm01.Quench.070515160107.714	42	20972	20	-0.0055	7.73	HcoilHcoil	IC_IS31	0.0008	2.160	2.159	quench 42 at I=20958.3A, T=2.16K, ramp rate=20A/s.
lm01.Quench.070515165517.079	43										We lost quench data for this ramp
lm01.Quench.070515174047.857	44	20855	20	-0.0067	8.25	HcoilHcoil	11LEL_11LER	0.0011	2.161	2.159	quench 44, I=20838.5A, T=2.16K, Ramp rate 20A/s.
lm01.Quench.070515182610.582	45	21499	20	-0.0095	9.94	WcoilIdot	11LEL_11LER	0.0011	2.160	2.159	quench 45 at I=21482A, T=2.16K, ramp rate=20A/s.
lm01.Quench.070515191824.882	46	21463	20	-0.0057	8.22	HcoilHcoil	11LEL_11LER	0.0010	2.160	2.159	quench 46 at I=21448.9A, T=2.16K, ramp rate=20A/s.
lm01.Quench.070515201218.747	47	21229	19	-0.0015	6.08	WcoilIdot	11REL_CC	-0.0025	2.160	2.159	quench 47 at I=21220.7A, T=2.16K, ramp rate=20A/s.
lm01.Quench.070516114740.183	48	20955	20	-0.0028	6.6	WcoilGnd	11LER_11RER	-0.0021	4.468	4.462	quench 48 at I=20940.8A, T=4.45K, ramp rate 20A/s.
lm01.Quench.070516123959.956	49	20625	20	-0.0045	6.73	SlWcoil	IC_IS31	-0.0063	4.467	4.462	quench 49 at 20614.5A. T=4.45K, ramp rate 20A/s.
lm01.Quench.070516140233.559	50	20107	20	-0.0059	7.06	SlWcoil	IC_IS31	-0.0074	4.442	4.437	quench 50 I=20095A, T=4.45K, Ramp rate=20A/s.

Table1. LM01 quench history

4. Splice Resistance Measurements

Several quenches during the training at 4.5K temperature were detected at the VMTF superconducting leads. Some of them showed a voltage rise in the splice between NbTi and Nb_3Sn conductors on the inner layer. It was decided to measure splice resistance for both coil layers for farther investigation of the observed effect.

The splice voltages were measured as a function of magnet current to determine their resistance. A calibrated Helwet-Packard 3458 Digital Multimeter (DVM) was used to digitize the raw (unamplified) splice voltages. DVM was programmed to integrate over 44 power line cycles in order to reduce 60 Hz noise components. We measured splice resistance at the inner layer first and then at the outer layer of the coil using the front input of the DVM. Table 2 shows the current and raw voltage data.

	I (A)	V(inner), mV	V(outer), mV
1	2000.1	0.0163	0.00252
2	3000.6	0.0166	0.00258
3	4000.6	0.0171	0.00264
4	5000.9	0.0176	0.00268
5	7001.3	0.0182	0.00275
6	9001.7	0.0189	0.00277
7	11002.1	0.0198	0.00282
8	13002.5	0.0206	0.00296
9	15003.1	0.0214	0.0031
10	18003.6	0.0226	0.00322

Table 2. Current and raw voltage data for splices at the inner and outer coil layer

Data and the linear fit are shown in Fig.4 and Fig.5. Significant difference was found between the two splice resistances. Splice at the inner layer seems to have one order larger resistance (0.393 ± 0.002) nΩ than the splice at the outer layer of the coil.

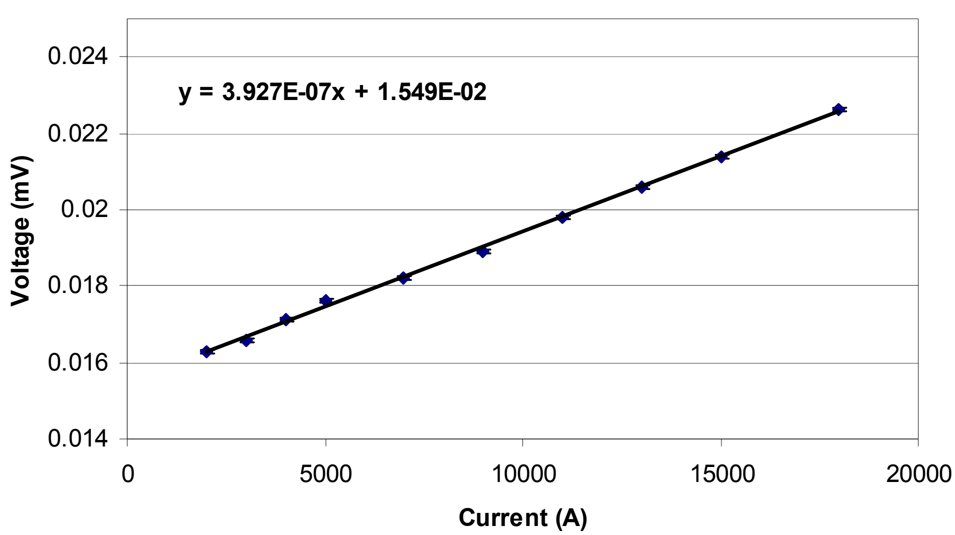

Fig.4 VA-dependence for the inner layer splice: data (dots) and linear fit (line)

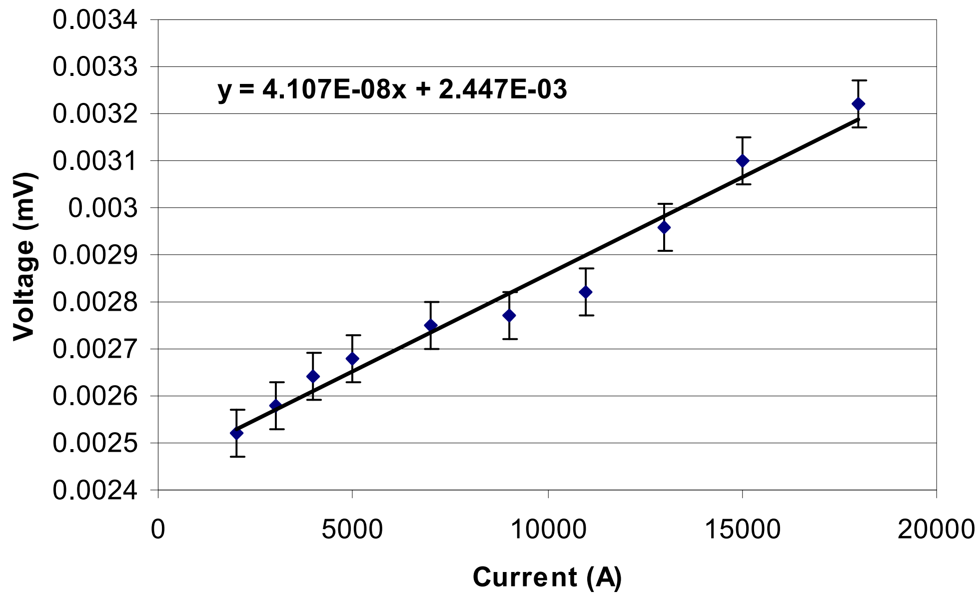

Fig.5 VA-dependence for the outer layer splice: data (dots) and linear fit (line)

5. Measurement of the Residual Resistance Ratio (RRR)

Estimates of RRR in LM01 coil segments have been made using data captured during the initial cool down of the magnet.

Voltages across "fixed" and "configurable" voltage tap segments were monitored by the Pentek data loggers, while a current of alternating polarity, +/- 10A, was put through the magnet. At room temperature (300K) we used the regular amplifier gain for the voltage tap segments, while at 20K we switched to the RRR-configuration, i.e. configuration with increased gains for the "fixed" and "configurable" voltage tap segments.

Data for all segments are shown in Fig.6 and Table 3. All CVT segments with their length are shown in Table 4.

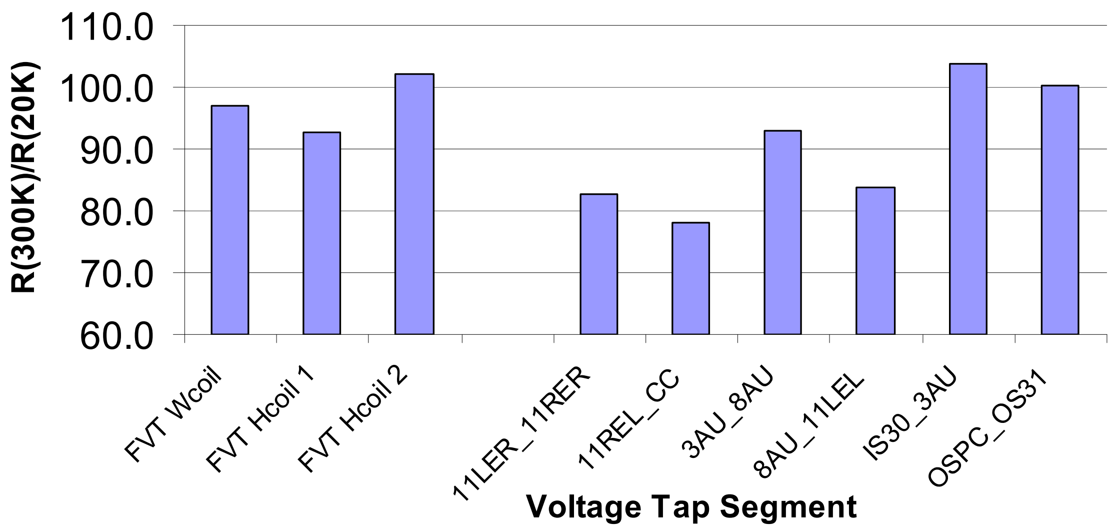

Fig.6 RRR data for different voltage tap segments (FVT and CVT)

Segment	V at 300K		V at 20K		I at 300K		I at 20K		300K			20K			
	+10A	-10A	+10A	-10A	+10A	-10A	+10A	-10A	ΔV	ΔI	R	ΔV	ΔI	R	**R300K/ R20K**
FVT Wcoil	1.504	-1.043	-0.0181	-0.04437	9.345	-11.09	9.33	-11.107	2.547	20.435	0.124639	0.02627	20.437	0.001285	97.0
FVT Hcoil 1	-0.12	-1.291	-0.0048	-0.01745	9.345	-11.09	9.33	-11.107	1.171	20.435	0.057304	0.01265	20.437	0.000619	92.6
FVT Hcoil 2	1.0315	-0.3737	0.01933	0.00557	9.345	-11.09	9.33	-11.107	1.4052	20.435	0.068764	0.01376	20.437	0.000673	102.1
11LER_ 11RER	0.01648	-0.0318	0.000213	-0.00037	9.345	-11.09	9.33	-11.107	0.04828	20.435	0.002363	0.000583	20.437	2.85E-05	82.8
11REL_CC	0.013	-0.02794	0.00014	-0.00039	9.345	-11.09	9.33	-11.107	0.04094	20.435	0.002003	0.000525	20.437	2.57E-05	78.0
3AU_8AU	0.2138	-0.32065	0.00256	-0.00319	9.345	-11.09	9.33	-11.107	0.53445	20.435	0.026154	0.00575	20.437	0.000281	93.0
8AU_11LEL	0.1134	-0.0898	0.000934	-0.00149	9.345	-11.09	9.33	-11.107	0.2032	20.435	0.009944	0.002424	20.437	0.000119	83.8
IS30_3AU	0.15	-0.1842	0.0014	-0.00182	9.345	-11.09	9.33	-11.107	0.3342	20.435	0.016354	0.00322	20.437	0.000158	103.8
OSPC_OS31	0.5815	-0.822	0.0059	-0.00809	9.345	-11.09	9.33	-11.107	1.4035	20.435	0.068681	0.01399	20.437	0.000685	100.3

Table 3. RRR data for all segments (with length more than 6 cm)

Segment	Length in inches	Length in cm
11LEL_11LER	2.5	6.4
11LER_11RER	62.125	157.8
11REL_CC	54.5	138.4
11RER_11REL	2.17	5.5
3AU_8AU	687	1744.9
8AU_11LEL	258.41	656.4
IC_IS31	2	5.1
IS30_3AU	437	1109.9
OSPC_OS31	1854.1	4709.4

Table 4. All CVT segments with their length